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Influence of high intensity ion beam irradiation on impact toughness of 12Cr1MoV steel

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Abstract

The impact toughness of non-treated and irradiated 12Cr1MoV steel Charpy specimens has been studied in the range of temperatures from 20 C to 600 C. It was revealed that the ion beam treatment of steel deteriorates the impact toughness by 5–40 % at the tested temperature range. The physical regularities of irradiation effect on microhardness and hardness of the treated surface were investigated. It was also found out that irradiated specimens fracture via more brittle mechanism, which is related to both more severe stress–strain state at the notch tip and gradient alteration of properties in the subsurface layer.

Keywords: physical mesomechanics, impact toughness, fracture, ion beam treatment, 12Cr1MoV steel

1. Introduction

The tightened requirements for the reliability of thermal power stations arouse the necessity of accounting for the impact of operating conditions on material degradation, which in its turn is accompanied by the stiffening of the requirements for strength and cracking resistance of heatproof steels [Nykyforchyn et al. (2010), Balyts'kyi et al. (2009)].

To the present moment, superheater drums and steam lines manufactured from 12Cr1MoV steel and used at

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thermal power stations in Ukraine and Russia have almost worn out [Student et al. (2012)]. It is well known that long-term exploitation leads to the degradation of steam line metal, which is accompanied by increased yield strength and reduced ductility (impact toughness, cracking resistance, etc.). This conditions a specific relevance of the problem of evaluating the limit state of metal structures for making a decision on prolongation of lifetime, performing partial or extensive repairs, or abandonment [Student et al. (2012), Yasniy et al. (2011)].

One of the most informative and the least labor-intensive testing methods is the estimation of impact toughness. At the same time, the necessity to account for the influence of operation parameters—primarily high temperatures—on mechanical characteristics of a material significantly complicates their investigation.

Impact fracture of heatproof steels is characterized by the abundance of mechanisms responsible for plastic deformation and fracture; the change of mechanisms determines the transition from one stage of dynamic fracture to the subsequent one [Nykyforchyn et al. (2010), Balyts'kyi et al. (2009)]. The revealing of the regularities of dynamic fracture of a material under operational temperatures allows controlling these processes, prevent the fracture of structures, more reasonably treat the problem of prognosticating the durability at the stages of design and operation of parts used in thermal power equipment. The successful solution of such problem requires the implementation of pendulum impact testers to record diagrams of Charpy specimen impact loading.

The increase of mechanical properties of materials through surface hardening is of prominent scientific and practical interest, since it enhances the life of machine parts and structural elements [Samutigin et al. (1997), Gualco et al. (2010)]. The modification of the structure of surface layer can be performed both at the stage of part manufacturing and during repair. The surface hardening of metallurgical and power engineering materials provides for improved fatigue life evading the remarkable decrease of cracking resistance [Panin et al. (2015), Vlasov et al. (2015)]. In some cases, for instance, during laser-assisted shock-wave treatment, there is a dramatic (up to 2 times) increase of impact toughness of specimens with a hardened surface layer and a modified core [Yasnii et al. (2010)]. At the same time, surface treatment of ferrite–pearlite steels usually does not lead to increased impact toughness of a material; however, it allows considerably increasing its wear resistance and fatigue life.

In previous work [Panin et al. (2015)], a technique of highly intensive irradiation by Zr ion beam of 12Cr1MoV heat-proof steel was suggested. It was shown that such treatment leads to the softening of a surface layer over the depth up to 150 μm and to a certain increase of microhardness in the core of a sample. Such phenomenon is followed by the growth of ultimate tensile strength by 15 % and increase of fatigue life by 2–3 times. The study of the effect of such treatment on the resistance to impact fracture in the course of testing by pendulum impact tester is of considerable interest. Thus, the goal of the present work is to investigate the effect of temperatures from 20 C to 600 C on the mechanisms of impact fracture of 12Cr1MoV heatproof steel subjected to preliminary ion beam vacuum arc treatment implementing techniques described in [Panin et al. (2015), Vlasov et al. (2015)].

2. Methods

The tested specimens were cut from a pipe fragment with the diameter of 300 mm by electro spark cutting. Each specimen was subjected to standard thermal treatment, i.e. normalization at T = 960–980 °C and subsequent high-temperature tempering at T = 740–760 °C [Panin et al. (2015)]. Here in after, such treated specimens are referred to as initial specimens.

The ion beam irradiation of the specimens was carried out implementing a high-current vacuum arc source of metal ions ‘‘Kvant UVN-0.2” setup equipped with oil-free cryogenic evacuation system. The treatment of the specimens was initiated after reaching vacuum in the chamber higher than $5 \cdot 10^{-3}$ Pa by a continuous flux of zirconium ions with the energy of approximately 2,5 keV and the density of ion current of about 3 mA/cm^2. The substrate holder mounted on the object stage and holding specimens was included immediately into ion acceleration scheme instead of conventional extraction of a selected ion beam from an implanter. In this case, the acceleration of ions occurs in a dynamic self-organizing boundary layer represented by a double electric layer, which is formed on the surface of a specimen under negative potential. According to DT-8866 infrared pyrometer, during the treatment, the surface layer of the specimen was cyclically heated up to about 900 ºC.

The impact toughness was determined using Instron 450MPX motorized pendulum impact tester. The processing software allowed dividing the energy of specimen fracture into components through the conversion of ‘‘load vs. time” dependence (P–t) into a ”load vs. bend” dependence (P–S). The regularities of deformation and fracture were studied using fractograms of the fracture surface using LEO EVO 50 scanning electron microscope (Zeiss, Germany).

3. Investigation results

3.1. Metallography

The microstructure of the specimens of both types (untreated and irradiated), including those after testing at various temperatures (Fig. 1), was studied. It was shown that the increase of the temperature of impact testing did not affect the size of grain in initial specimens of d=28 μm, which corresponds well with heat-resistant properties of the studied steel. At the same time, the irradiated specimens have demonstrated the decrease of the grain size in core down to d=16 μm (Fig. 1b). The thickness of the modified surface layer varied from 130 to 200 μm. The average grain size in modified surface layer amounted to about 28 μm, i.e. it was approximately equal to that for non-irradiated specimens. The increase of testing temperature up to T=375 and further to T=600 ºC was not accompanied by the change in grain size in the core of irradiated specimens.

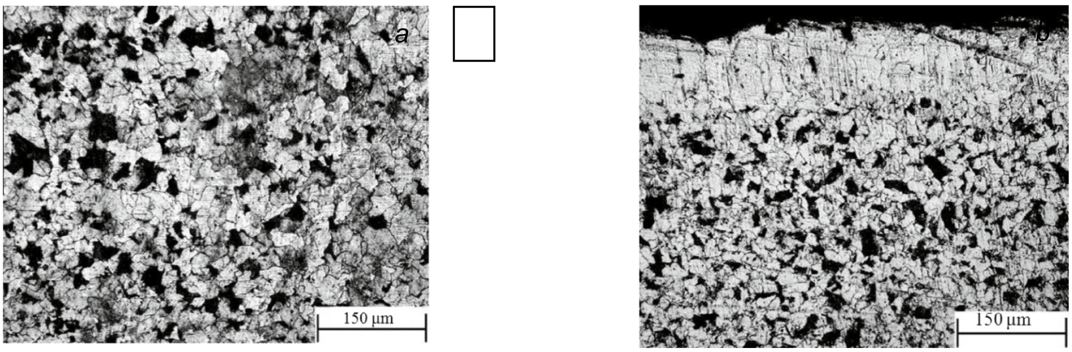


Fig. 1. Photographs of the cross-section of (a) as-supplied state specimens and (b) irradiated specimens.

3.2. Microhardness measurement

The study included the measurement of microhardness at the surface and over the cross-section of initial and irradiated specimens tested at different temperatures (Fig. 2). Apparently, all the specimens after the irradiation manifest reduced microhardness in surface layer over the depth of about 200 μm, which complies with data obtained by metallography (Fig. 1, b). Conversely, at the depth of 200–500 μm, the irradiated specimen at room temperature demonstrated increased microhardness, which is connected with cyclic thermal exposure at the specimens during irradiation. Such results also comply well with the metallography showing the decrease of grain size (Fig. 1, b).

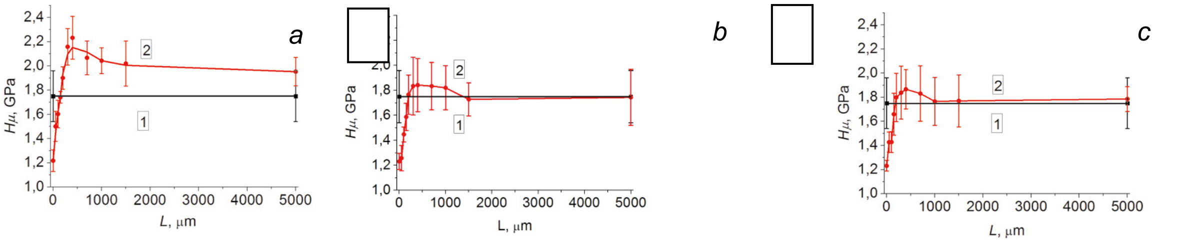


Fig. 2. Distribution of microhardness H as a function of distance L from the surface of Charpy specimens at different testing temperatures. (a) T=20 ºC; (b) T=375 ºC; and (c) T=600 ºC; untreated specimen (1); irradiated specimen (2).

The decrease of surface layer hardness that was noted even for specimens tested at *T*=20 ºC testifies its relation to the ion beam treatment and accompanying processes of high-temperature recovery and redistribution of alloying elements at elevated and high temperatures.

3.3. Impact toughness tests

The specimen fracture diagrams at different testing temperatures were recorded. The obtained data was used to determine the impact toughness *KCV* of specimens (Table 1). It was shown that *KCV* of the specimens after irradiation reduces depending on the testing temperature by 5–40 %. The largest reduction of this parameter was noted at *T*=20 ºC due to the embrittlement of core material caused by structure alteration during irradiation (which was established by microhardness measurement; see Figs. 2) and consequent reduction of crack propagation energy at dynamic loading (namely, at the stage of crack growth).

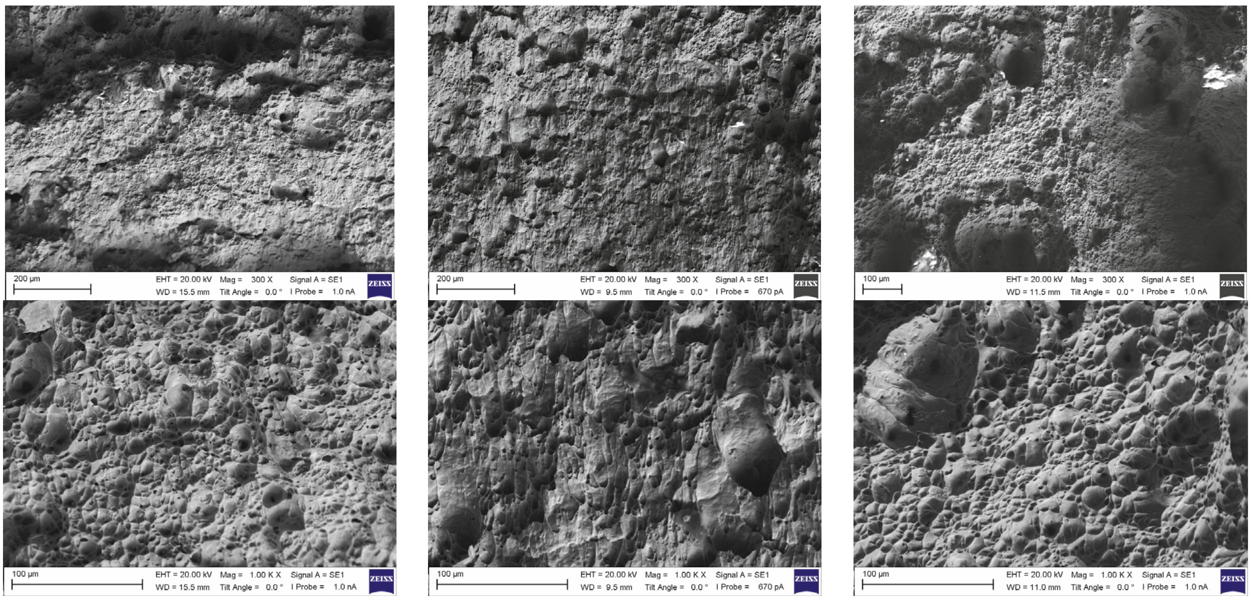
Table 1. Results of impact toughness testing of irradiated 12Cr1MoV steel specimens.

Testing temperature (*T*, ºC)	*KCV* untreated specimen, J/cm^2	*KCV* specimens after irradiation, J/cm^2
20	226	130 (↓ 42%)
375	190	152 (↓ 20%)
600	99	94 (↓ 5%)

4. Micromechanisms of fracture of irradiated specimens

4.1. Crack initiation zone

Testing temperature *T* = 20 ºC. In the irradiated specimen, the zone of crack initiation also has the signs of brittle-ductile fracture (Fig. 3a). Also, the fractogram of zone I has prominent differences of height in the fracture surface.



a b c

Fig. 3. Fracture surfaces in the zone of crack initiation in 12Cr1MoV steel after the modification after testing at *T*=20 ºC (a), *T*=375 ºC (b) and *T*=600 ºC (c) obtained at various magnification.

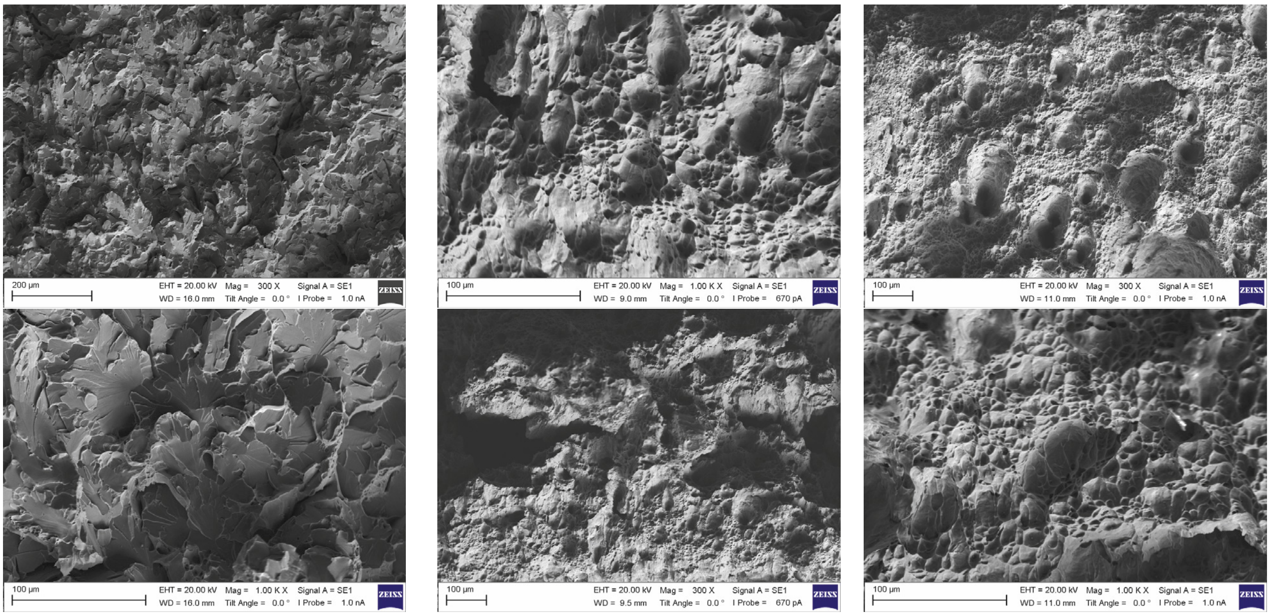
This must have been caused by the modification of the structure during the irradiation resulting in the formation of layers with different structure and mechanical properties (see measurements of microhardness and metallography in Figs. 1, 2), which can lead to the branching of a crack (especially in the case of fast impact fracture process) and formation of a similar stepped relief.

Testing temperature *T*=375 ºC. In the case of irradiated specimen, the fracture surface demonstrates appreciable height discontinuities; in several regions, the fracture is accompanied by tear-outs of the material (Fig. 3b). However, it should be noted that the size of such regions is rather small, which testifies the positive influence of elevated temperature on the initiation of relaxation processes.

High testing temperature *T*=600 ºC. At high testing temperature, for the irradiated specimens, a brittle-ductile fracture is typical with a multitude of tear-outs (sometimes such regions are large) and height discontinuities; the morphology of the surface is very rough, which testifies the evident inhomogeneity of deformation development at the stage of macrocrack initiation (Fig. 3c). The influence of high testing temperature also manifests as the oxidation of the surface (Fig. 3c).

4.2. Crack growth zone

Testing temperature *T*=20 ºC. In the specimen treated by the ion beam, the fracture surface is quasi-brittle (Fig. 4a); it is covered by brittle-ductile cleavages, which proves the brittle propagation of the crack. This process was accompanied by the opening of a multitude of cracks oriented in perpendicular to the front of its propagation.



a b c

Fig. 4. Fracture surfaces in the zone of crack propagation of 12Cr1MoV steel specimens subjected to the ion beam treatment at impact testing temperatures of *T*=20 ºC (a), *T*=375 ºC (b) and *T*=600 ºC (c) obtained at various magnification.

Testing temperature *T*=375 ºC. The fracture surface of the irradiated specimen is characterized by the fracture with coarse-grain structure (Fig. 4b), which is typical for the conditions of crack propagation along grain boundaries, and a zone of fibrous (ductile) fracture with matte rough surface and signs of local plastic deformation. Thus, the signs of brittle fracture—typical for room testing temperature—are absent. However, another nonuniformity of fracture surface is evident. Along with shallow dimples of quasi-ductile fracture, there are large craters caused by material tear-out.

Testing temperature T=600 ºC. After the ion beam treatment, the fracture surface has localized sections of dent-like fracture of round shape (Fig. 4c). The surface between such local fracture centers is covered with shallow dimples, which are more than 10 times smaller. In general, it can be concluded that the character of fracture surfaces of irradiated and non-treated specimens at room testing temperature looks similar.

In the irradiated specimens, as compared to non-irradiated material, the fracture mechanism is more brittle, which is related both to more severe stress–strain state in the notch tip and with the presence of locally hardened regions. Evidently, more severe stress–strain state affects the reduction of ultimate plastic deformation, which is further confirmed by a sharper inclination of the falling section of the deformation diagram.

5. Conclusions

The present study develops an approach based on the description of elastic–plastic deformation of Charpy specimens subjected to impact loading at the stages of crack initiation and propagation under conditions of normal, elevated and high temperatures.

It was found that the nonuniformity of specimen structure modified by the ion beam treatment plays dominating role in plastic deformation and consequent impact fracture of Charpy specimens.

The basic regularities of testing temperature influence on the impact toughness of 12Cr1MoV steel were established. At T=20 ºC, the energy of fracture decreased by 42%; at T=375 ºC, by 20% and at T=600 ºC, by 5%.

Using the methods of scanning electron microscopy, the reduction of fracture ductility for modified specimens was established and justified. It was demonstrated that impact loading of heatproof steel with the zones of local hardening increases the severity of the stress–strain state, which conditions the localization of deformation at meso-level and leads to increased brittle component during the fracture of specimens.

The practical importance of the obtained results is the ability to use them for analyzing the reliability of the zones of thermal influence of welding seams of heatproof steels used in electric power industry equipment.

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References

Nykyforchyn, H. M., Student, O. Z., Krechkovs'ka, H. V., Markov, A. D., 2010.Evaluation of the influence of shutdowns of a technological process on changes in the in-service state of the metal of main steam pipelines of thermal power plants. Materials Science, 46(2), 177-189.

Balyts'kyi, O.I., Ripei, I.V., Onyshchak, O.Ya., 2009. Variations of the impact toughness of 12Kh1MF steel in operating steam pipelines of thermal power plants. Materials Science, 45(6), 826-830.

Student, O. Z., Svirs'ka, L. M., Dzioba, I. R., 2012. Influence of the long-term operation of 12Kh1M1F steel from different zones of a bend of steam pipeline of a thermal power plant on its mechanical characteristics. Materials Science, 48(2), 239-246.

Yasniy, P.V., Maruschak, P.O., Panin, S.V., Bischak, R.T., Vuherer, T., Ovechkin, B.B., Panin V.E., 2011. Temperature effect on impact fracture of 25CrlMolV ferrite-pearlite steel. Physical Mesomechanics, 14(3–4), 185-194.

Samotugin, S. S., Muratov, V. A., Koval'chuk, A. V., 1997. Plasma-jet hardening of annular tools. Metal Science and Heat Treatment, 39(10), 409-411.

Gualco, A., Svoboda, H.G., Surian, E.S., 2010. L.A.D. Vedia Effect of welding procedure on wear behaviour of a modified martensitic tool steel hardfacing deposit. Materials and Design, 31(9), 4165-4173.

Panin, S.V., Vlasov, I.V., Sergeev, V.P., Maruschak, P.O., Sunder, R., Ovechkin, B.B., 2015. Fatigue life improvement of 12Cr1MoV steel by irradiation with Zr+ ion beam. International Journal of Fatigue, 76, 3–10.

Vlasov, I., Panin, S., Sergeev, V., Lyubutin, P., Bogdanov, O., Maruschak, P., Ovechkin, B., Menou, A., 2015. Surface layer modification of 12Cr1MoV and 30CrMnSiNi2 steels by Zr+ ion beam to improve the fatigue durability. Procedia Technology, 19, 313-319.

Yasnii, P. V., Marushchak, P.O., Nikiforov, Yu.M., Hlad'o, V.B., Kovalyuk, B.P., 2010. Influence of laser shock-wave treatment on the impact toughness of heat-resistant steels. Materials Science, 46, 425-429.